Technical Report No. 32-690

AC Ratio Transformer Technique for Precision Insertion Loss Measurements

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A simple high-precision insertion loss measuring system has been developed which can be made to approach the accuracy of a high-quality standard ratio transformer. It is believed that an over-all accuracy of ± 0.003 db has been obtained for a measurement of approximately 0.5 db. Relative accuracies to 0.001 db should be obtainable at this level. Detection is accomplished by means of a conventional dual-channel bolometer system; comparison is by an ac ratio transformer. Because of the normal bolometer limitations, measurements in one step are limited to insertion loss values of 20 to 30 db. Excellent agreement was obtained between measured and theoretical attenuations of specially developed rotary vane attenuators.

author

I. INTRODUCTION

At the Jet Propulsion Laboratory, the need has existed for higher-precision microwave measurements in order to achieve more accurate calibrations of large antenna systems. Transmission line measurement tolerances become extremely critical when the transmission line is part of a low-noise maser system. Tolerances are even more critical in the transmission line measurements necessary to determine the effective noise temperature of a reference noise source such as a gas tube or a cryogenic cooled termination. Often a requirement exists to perform ultraprecise measurements on a transmission line system which is installed on one of the large Deep Space Instrumentation Facility antennas. The basic need is best laboratory accuracy in a portable, reliable, and fieldworthy test instrument.

Techniques have been developed which we believe will satisfy the above requirements for reflection coefficient and insertion loss measurements. Reflection coefficient measurement instrumentation will not be discussed in this report beyond mentioning that precision reflectometer techniques can meet the requirements. Ultraprecise insertion loss measurements are achieved by means of a new type of insertion loss test set developed by the authors. Results of this development were initially reported in August 1963 (Ref. 1).

Some thought has been given to the possibility of using superheterodyne insertion loss systems with a high-precision, 30-Mc attenuator. The National Bureau of Standards (NBS) has relied on this type of system for most insertion loss calibrations. The high-precision NBS 30-Mc attenuator is expensive to manufacture, although drawings and engineering details have been made available. There are now several high-precision, 30-Mc insertion loss systems commercially available. These systems are not intended for field use, however. Engen and Beatty (Ref. 2) describe a method of performing relative attenuation measurements to accuracies from 0.0001 to 0.06 db over a range of 0.01 to 50 db. Again, this does not appear to be a system adaptable to field use. Other insertion loss devices will not be described; a partial list of references is included (Refs. 3–7).

One basic idea for an improved insertion loss set was the inclusion of a ratio transformer in the system. A ratio transformer is simply a very high-precision ac voltage divider. Voltage division is determined by the turns ratio, and commercially available units may be obtained with accuracies of better than 1 part in 10^5. In addition, ratio transformers have a high input impedance, a low output impedance, low phase shift, and operate quite well at 1000 cps. This frequency is convenient because of the variety of available signal generators that are modulated at 1000 cps. The ratio transformer is commonly used as a standard to calibrate ac resistive voltage dividers; it seemed desirable to eliminate this step and use the standard directly as the measurement device.

Because of a considerable familiarity with the Weinschel dual-channel insertion loss set, an initial attempt was made to modify this set to include a ratio transformer. It was found that resolution to about 0.001 db could be obtained, but that stability and repeatability did not approach this level. Probably by improving the amplitude stability of the particular standard BA-1 and BA-5 amplifiers used for the test, the problem could have been corrected. The advantages of a dual channel system are well recognized; they are described in the Weinschel Engineering Co., Inc. literature and in Refs. 4 and 6. For measurements in the field of extremely low values of insertion loss, a dual channel system is almost mandatory to reduce source amplitude instability effects.

Because any dual-channel system incorporating amplifier electronics in one or both of the bridge arms is inherently subject to instabilities, an approach was tried which involved eliminating bridge arm electronics entirely and nulling directly at low level. Perhaps this approach was not attempted previously because of concern over the problems of keeping circuit losses and added noise (such as pickup noise) low at the amplifier input. Also, isolation and loading of the ratio transformer or reference standard device must be considered.

II. DESIGN OF THE RATIO TRANSFORMER INSERTION LOSS SET

The definition of the insertion loss of an apparatus (*IRE Standards on Antennas and Waveguides, 1953*) is "the ratio, expressed in decibels, of the power received at the load before insertion of the apparatus, to the power received at the load after insertion." The more restrictive definition of insertion loss adopted by the IRE in 1959 is, "the change in load power, due to the insertion of a waveguide component at some point in a transmission system, where the specified input and output waveguides connected to the component are reflectionless looking in both directions from the component (match-terminated)."

A. Principle of Operation

The technique described in this report uses an audio substitution principle for insertion loss measurements. An accurate ac ratio transformer is used as the audio frequency attenuation standard. Figure 1 shows a block diagram of the test setup. The rf signal generator is 100% square-wave-modulated at 1000 cps. Detection is accomplished by means of a dual-channel bolometer system. The rf power delivered to the test bolometer is simultaneously compared to the rf power delivered to the reference bolometer. Any amplitude changes in the output of the rf signal generator changes the power in the respective channels in the same proportion so that the power ratio remains constant.

If the bolometers for the test set are truly square law detectors, comparisons may be made of their detected ac voltages to give the ratio of the rf power levels at the reference and test bolometers. Comparison of the detected ac reference and test signals is accomplished by a null detection scheme. The divided reference signal voltage developed across the output terminals of the ratio transformer is used to buck the test voltage developed across the bridge transformer input terminal and ground (Fig. 2).

The operating procedure is to adjust the ratio transformer setting and phase shift capacitors until a null occurs in the bridge transformer output. At this null condition, the ratio of the test to the reference signal is equal to the dial setting of the ratio transformer. This ratio of test to reference signals is determined before and after insertion of the test item in the rf system. The rf power ratios indicated on the ratio transformer dial before and

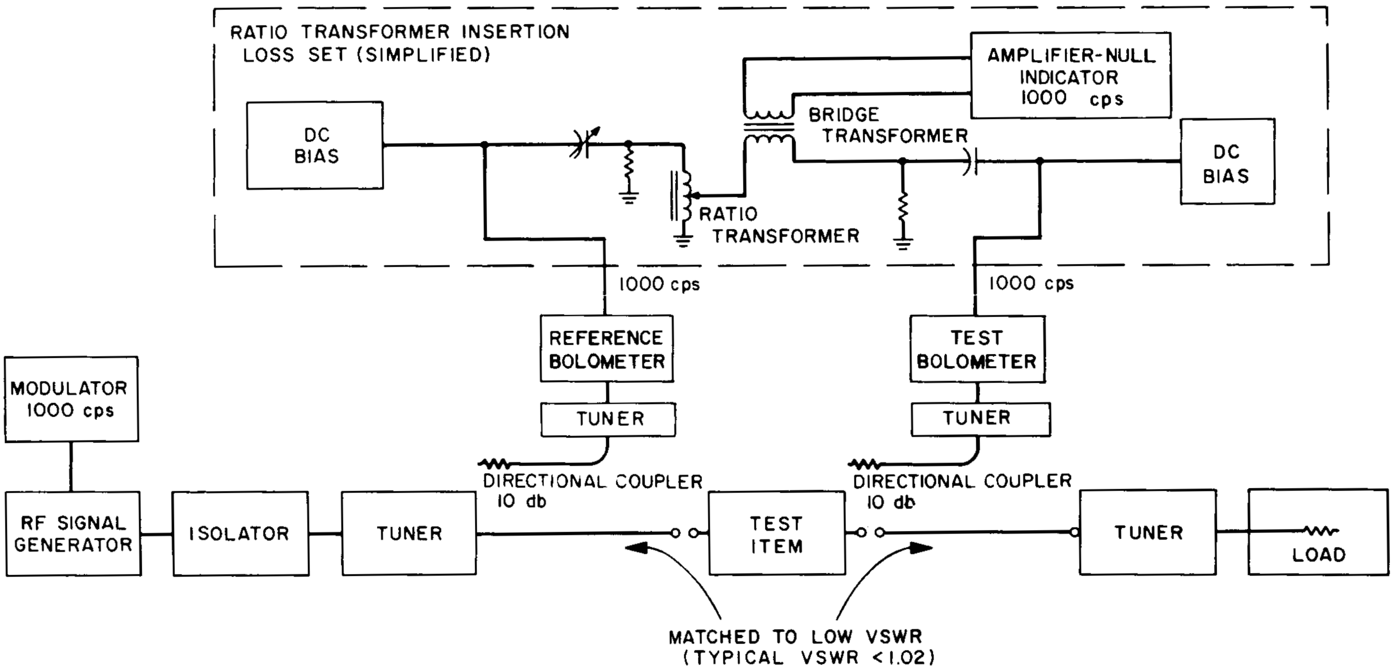

Fig. 1. Test setup block diagram

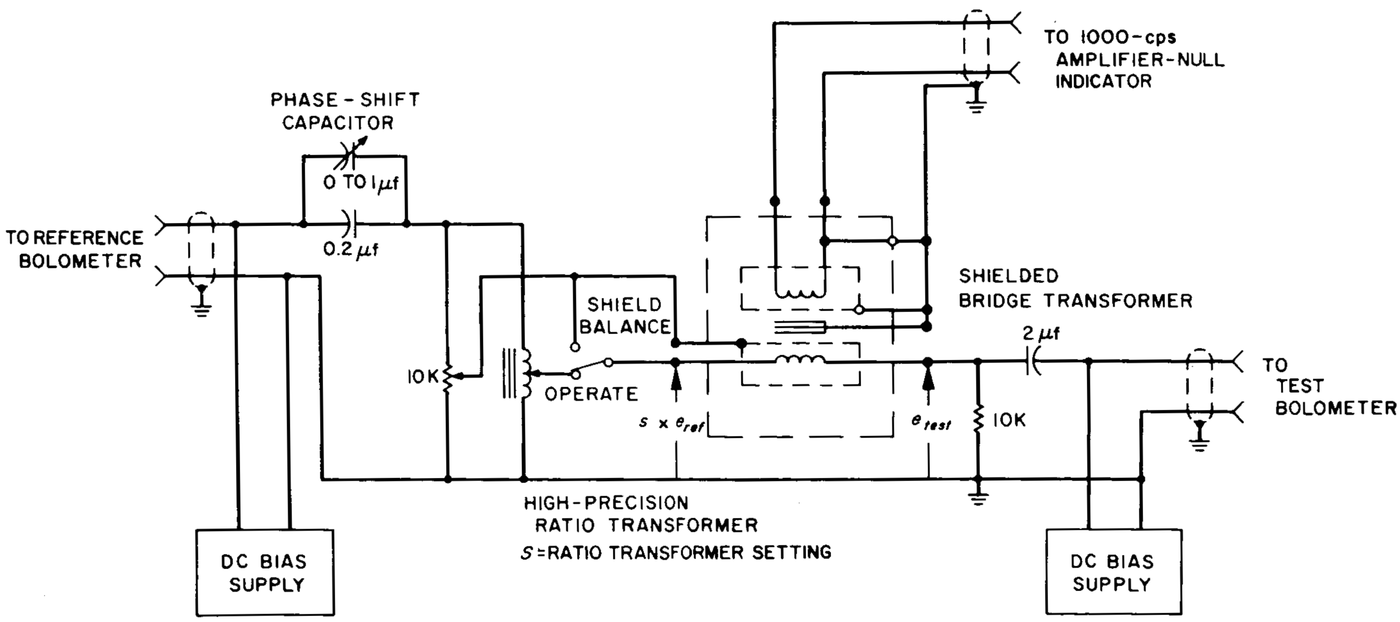

Fig. 2. Diagram of ratio transformer insertion loss set

after insertion are each converted to decibels with the use of conversion tables. The difference of the db values gives the insertion loss of the test item in db.

B. Bolometers

Bolometer nonlinearity provides the basic limitation on the accuracy for a one-step measurement. (The authors use the term "bolometer linearity" to describe the characteristic where the bolometer ac output voltage is directly proportional to the rf power into the bolometer. This characteristic is generally referred to as the bolometer square law characteristic. "Bolometer nonlinearity" is used here to describe departure from square law characteristics.) Two bolometer types which have been used successfully in the insertion loss set are the Narda N603 and Sperry 821 barretters. These bolometers are biased with approximately 8.75 ma dc current, and the operating ac resistances are approximately 200 ohms. For a measurement of 30 db at an initial power level of 100 μw, the error due to bolometer nonlinearity should be less than 0.03 db. For a careful measurement of 0.2 db at the same power level, the maximum error is less than 0.001 db due to nonlinearity.

Figure 2 is a schematic diagram of the calibration and null detection system. In order to achieve approximately equal and constant ac load impedances for the two bolometers (looking into the network from the respective bolometer outputs), a 10-kohm input resistor is used for the test bolometer and a 10-kohm potentiometer is used for the reference bolometer. The wiper arm of the 10-kohm potentiometer is connected to the shield for the primary windings of the bridge transformer. The impedance formed by the primary shield capacitance to ground is a high impedance (typically equal to or greater than 250 kohm at 1 kc). For a first-order approximation, the impedances across the coupling and phase shift capacitors are neglected so that the ac load impedance of each bolometer can be considered to be effectively 10 kohms.

The error in attenuation measurements caused by "voltage transfer errors" (Ref. 3) due to the finite 10-kohm load impedances for the bolometers can be considered to be negligible for most typical operating conditions. For a typical bolometer with an operating ac resistance of 200 ohms and a sensitivity of 4.5 ohms/mw with less than 0.2 mw peak rf power into the bolometers, the maximum voltage transfer error for this insertion loss system is about 0.0004 db.

C. DC Bias Supplies

The dc bias supply for each bolometer consisted of a Dressen-Barnes Electronics Corporation (Pasadena, Calif.) Model 12-103 power supply in series with a fixed 20-kohm resistor and coarse and fine control potentiometers. Separate bias supplies for each bolometer were provided to maintain good isolation. Analysis showed that this dc bias supply circuit approaches a constant current source, since a change in resistance of the bolometer over the normal operating range will cause a maximum current change of only 0.005%. This analysis is based on bolometers having characteristics similar to the Narda N603 and Sperry 821 barretters and an initial rf power level setting of less than 0.2 mw peak power.

D. Ratio Transformer

The ratio transformer and bridge transformer nulling system were capacitively coupled to the bolometers for dc isolation. Several companies manufacture high-precision ratio transformers. During the development, the Electro Scientific Industries Corporation (ESI) Model DT-45 and the Gertsch Products Inc. Model RT-7 were tested with no noticeable difference in accuracy. The minimum input impedance of these ratio transformers is typically 100 kohms at 1 kc. The minimum load impedance for the ratio transformer at 1 kc is, to a good approximation, the impedance reflected into the primary terminals of the shielded bridge transformer in series with 200 ohms of the test bolometer. If the divided reference signal voltage, $s \times e_{ref}$ (see Fig. 2), developed across the output of the ratio transformer, and the test signal voltage, e_{test}, are equal in amplitude and phase, a null is produced at the output of the bridge transformer. At this null condition, the effective loading on the ratio transformer is zero. The combination of zero loading and a low output impedance for the ratio transformer helps maintain the output accuracy.

E. Bridge Transformer

A high-quality shielded bridge transformer (Gertsch Model ST-248) was used for the nulling device. To achieve a very deep null, the electrostatic shield for the primary winding of the bridge transformer is connected to the 10-kohm potentiometer. A small voltage applied to this shield is adjusted to cancel any remaining bridge transformer leakage currents.

Recent tests at the time of this writing indicated that when a double-shielded transformer (such as the Gertsch Model ST-100) was used as the bridge transformer, the primary shield of the bridge transformer could be tied directly to the wiper arm of the ratio transformer without any noticeable loading effects or degradation of measurement accuracy (Ref. 8). It was possible to replace the shield balance potentiometer with a fixed 10-kohm resistor and eliminate a step in the operation.

F. Output Indicator

The output of the bridge transformer may be coupled to a high-quality commercial standing-wave indicator to satisfy the requirement of high-gain, narrow-bandwidth amplification of the null signal and a suitable indication of the signal. The choice of operating at either 200-ohm "crystal" or 220-kohm input impedance of the indicator was dependent upon the turns ratio of the bridge transformer and the best null condition determined experimentally. Resolution of the system is improved by using a very narrow bandwidth, consistent with the frequency stability of the modulator. Commercial standing-wave indicators are somewhat elaborate for this application but are normally available in a microwave laboratory.

G. Phase Shifter

Generally there exists a small amount of audio-frequency phase shift in the system. In order to correct this to obtain the best null, we use a set of decade capacitors. The value of phase shift difference will vary when bolometers are changed. During an actual measurement, when large values of insertion loss are inserted and removed, the capacitance change required corresponds to a phase shift of a small fraction of 1 deg. This capacitance change will produce a small change in the amplitude of the reference signal output. An error calculation indicates that the phase shift capacitance change normally required will have negligible effect on the insertion loss measurement accuracy. To limit the insertion loss measurement error (contributed by the phase shifter) to 0.001 db maximum, the total capacitance of the phase shift capacitors should not be operated at less than 0.2 μf, and the capacitance change required for nulling after the test device is inserted should not be greater than 0.005 μf. For most commercial bolometers tested in this system, it was possible to obtain the initial null with a total phase shift capacitance of 0.5 μf or greater. Although a more sophisticated phase shifter circuit can be used, the present design is felt to be adequate for its purpose.

H. Factors Influencing Accuracy

If the rf input signal into the bolometers is square-wave modulated, the time constants of the bolometers will cause distortion of the ac output wave forms (Ref. 5). Harmonics of the 1-kc signal will appear at the output of the bridge transformer. However, because of the use of suitable filtering in the output indicator, these harmonics have not been a significant problem.

The design of the insertion loss set is sufficiently good at this time so that only difficulties external to the ratio transformer setup are noticeable. At times, the thermal environment of the bolometers can become critical. During field use in particular, it is found that the rf test setup and bolometers must be brought into thermal equilibrium with the items under test. This is required in the laboratory, also, but is not such a significant effect. Consideration has been given to liquid cooling the bolometers for temperature stability, utilizing a method similar to the NBS method of cooling klystrons. So far, however, this has not been attempted and probably it is not required. Standard precautions must be taken to prevent the generation of ground loops. Also, great care must be taken in the use of waveguide flanges or coaxial connectors for the test item and for the directional couplers on each side of the insertion test point.

I. Field-Type Test Setup

Figures 3 and 4 show the S-band waveguide test setup. The setup is a hybrid waveguide and coaxial directional coupler combination: a compact and convenient design

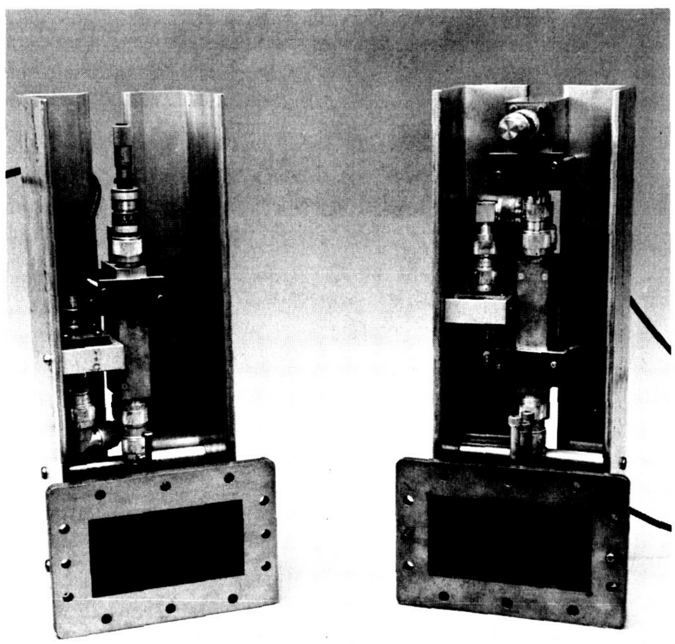

Fig. 3. S-band waveguide test setup, front view

for field use. Aluminum angle brackets are used to provide support and to prevent flexing of the coaxial connectors during tilting of the test setup. The brackets also provide a good heat sink for the bolometers. Tuning is provided by means of a triple stub tuner built into each waveguide transition. A high isolation circulator is used to prevent source impedance variations from affecting the match at the test point.

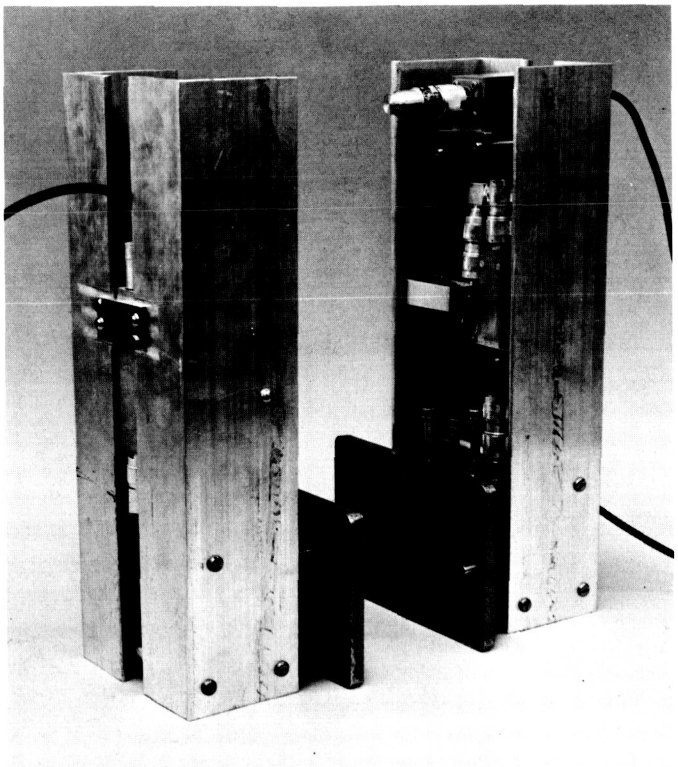

Fig. 4. S-band waveguide test setup, side view

III. CALIBRATION AND TESTING

Testing and evaluation of the insertion loss system have been in progress for 3 years. Upper limits of potential errors due to circuit loading and bolometer nonlinearity can be calculated. By a combination of observation and calculation, potential errors may be estimated for other causes such as phase shifter amplitude changes, 1000-cps waveform distortion, output impedance changes, and amplitude drifts due to thermal and bias current changes. The effect of some other potential error sources, such as leakage, is difficult to estimate. Therefore, methods of empirical evaluation have been tried, using microwave devices as reference standards.

A. *Rigid Coaxial Line Standards*

Figure 5 shows a set of rigid coaxial lines fabricated from stainless-steel tubing. These lines have been used as low-value coaxial attenuators for calibration of low-noise systems at 960 Mc. The 960-Mc rf setup was the most convenient to use at the start of this development. A medium-length line was calibrated and then used for testing the insertion loss set for stability and resetability. The standard Type N connectors at the test point and on the rigid coaxial lines caused some difficulty, although the center pin location tolerances were held quite close. The calibration of stainless-steel rigid coaxial line No. 2 (Fig. 5) was 0.155 ± 0.015 db. Tolerances for this type of rigid line could be improved considerably by use of the new precision Blue Dot Type N connectors (Ref. 9).

B. *Rigid Waveguide Standards*

Figure 6 shows a set of standard X-band waveguides fabricated from copper, aluminum, and stainless-steel tubing. The lengths of the various waveguides are listed in Table 1. Tolerances on the waveguides are approximately ±0.002 in., but the relative tolerances between waveguides of a particular material are somewhat better. Table 1 presents a summary of data obtained on the rigid waveguides at 8448 Mc. Each measured value in Table 1 represents the average of several individual measurements as in Table 2. Column 1 of Table 1 presents a calculated value for insertion loss for the copper and aluminum waveguides. Column 2 presents the loss measured in January 1963, and Column 3 presents the loss measured in February 1963, after the waveguide flanges were reworked. Each value presented in Column 3 is the average of several measurements; the standard deviation of each set of measurements is also presented in Column 3. Mismatch errors for the insertion loss measurement were less than 0.001 db because the insertion loss setup was matched to a VSWR of 1.01 or less in either direction at the test point, and because the VSWR of the standard waveguides also was very good, less than 1.01. Also listed in Column 3 is an estimated maximum probable error for each set of waveguides, which is believed to cover the measurement resetability, possible mismatch error, and other sources of error in the instrumentation.

It is believed that the insertion loss of the longest stainless-steel waveguide is 0.503 db and is accurate to

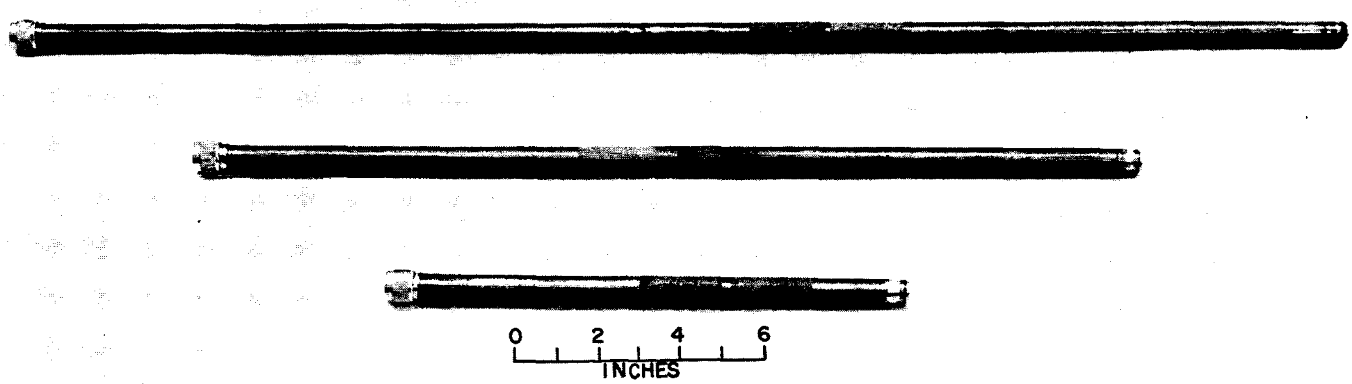

Fig. 5. Low-value coaxial attenuators constructed from commercial stainless-steel tubing

Table 1. Insertion loss measurements of copper, aluminum, and stainless-steel rigid waveguides

	1	2	3			4	5	6	7
Copper, in.	Theoretical loss, db	Measured loss, L, db Jan 63	Measured loss, (L'), db Feb 63	Standard deviation, db	Estimated probable error (total), db	Difference between 1 and 3, db	Difference between 2 and 3, db	$\frac{L'_{C_1}}{S_{C_1}}$ $(S_{C_2}; S_{C_3}; S_{C_4})$ db	Difference between 3 and 6, db
C_1 12.00	0.0403	0.0467	0.0412	±0.0011	±0.002	0.0009	−0.0055		
C_2 12.33	0.0413	0.0441	0.0444	±0.0013	±0.002	0.0031	0.0003	0.0423	−0.0021
C_3 18.00	0.0603	0.0644	0.0634	±0.0015	±0.002	0.0031	−0.0010	0.0617	−0.0017
C_4 24.00	0.0806	0.0865	0.0830	±0.0011	±0.002	0.0024	−0.0035	0.0820	−0.0010
Aluminum, in.								$\frac{L_{A_1}}{S_{A_1}}$ $(S_{A_2}; S_{A_3}; S_{A_4})$	
A_1 12.00	0.0503	0.0663	0.0617	±0.0013	±0.003	0.0114	−0.0046		
A_2 12.33	0.0516	0.0732	0.0646	±0.0026	±0.003	0.0130	−0.0086	0.0634	−0.0012
A_3 18.00	0.0754	0.0921	0.0915	±0.0018	±0.003	0.0161	−0.0006	0.0925	0.0010
A_4 24.00	0.1005	0.1323	0.1205	±0.0008	±0.003	0.0200	−0.0118	0.1232	0.0027
Stainless steel, in.								$\frac{L'_{S_1}}{S_{S_1}}$ $(S_{S_2}; S_{S_3}; S_{S_4})$	
S_1 11.23		0.2464	0.2471	±0.0014	±0.003		0.0007		
S_2 11.54		0.2517	0.2520	±0.0010	±0.003		0.0003	0.2540	0.0020
S_3 17.24		0.3755	0.3774	±0.0003	±0.003		0.0019	0.3790	0.0016
S_4 23.23		0.5045	0.5031	±0.0021	±0.003		−0.0014	0.5111	0.0080

NOTES:

1. Operating frequency, 8448 Mc.
2. Physical difference in the waveguide between measured loss (January 1963) and measured loss (February 1963).
   Copper: flanges lapped; inside cleaned and polished.
   Aluminum: flanges lapped.
   Stainless steel: flanges lapped.
3. Symbols
   L = measured loss (January 1963); L' = measured loss (February 1963); S = length.
   Column 6 shows how the loss should increase as the length increases, using the measured losses of the shortest lengths of waveguide as a reference.
   S_{C_1} = length of C_1, etc.

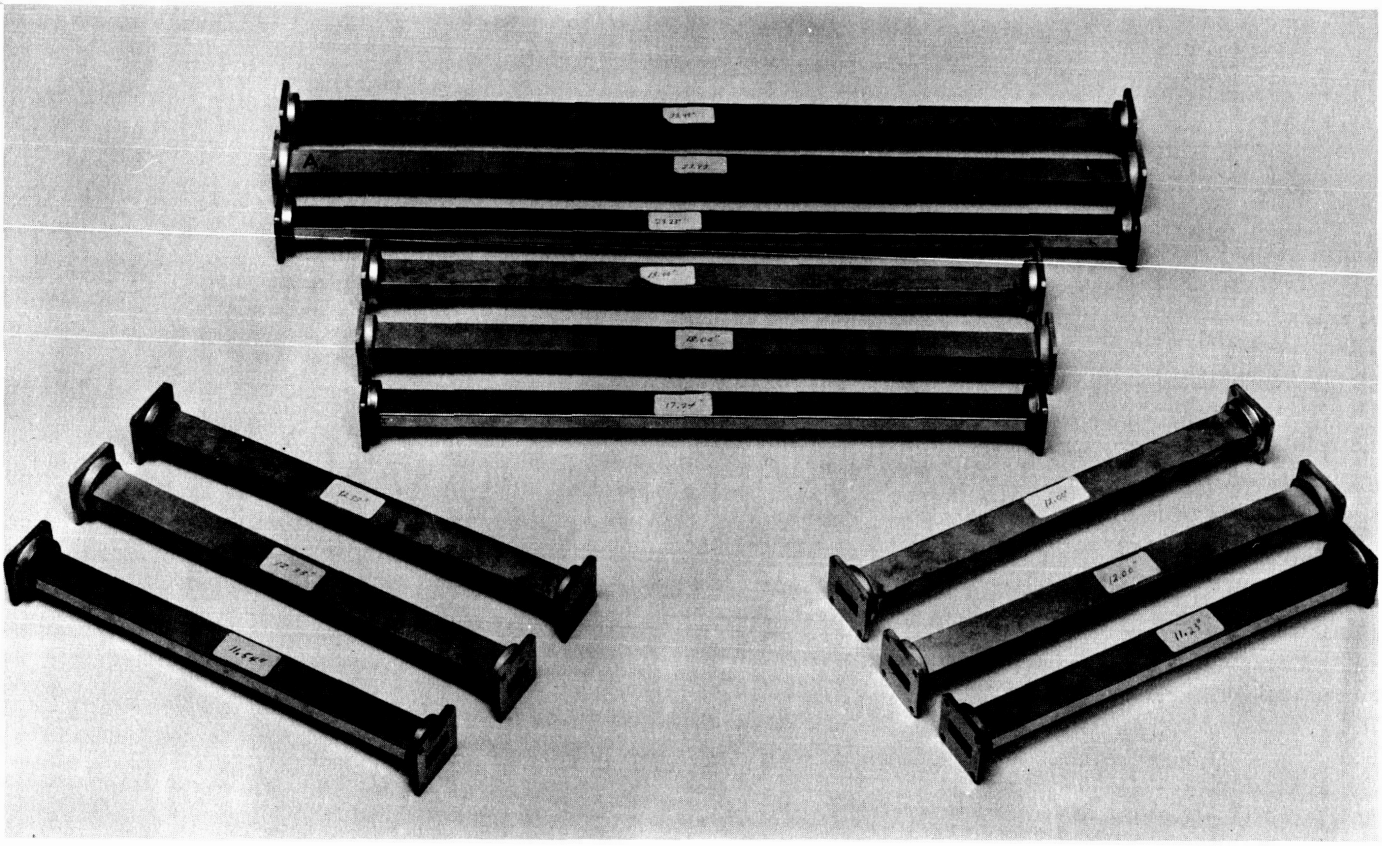

Fig. 6. Standard X-band waveguides

±0.003 db. As a matter of interest, a comparison is made in Column 4 between the loss measured in February 1963 and the theoretical loss calculated in Column 1. At X-band frequencies, surface roughness significantly affects the insertion loss, which is probably the reason for the large difference between measured and calculated loss. Column 5 presents the difference between the measurements performed in January and February of 1963, showing the results of the flange improvements. The shortest copper and aluminum waveguides appeared to be improved by approximately 0.005 db each. Differences of about 0.001 db or less are not considered to be significant. Flange scratches were noticed and removed on some of the aluminum waveguide flanges, and the 24-in. aluminum waveguide section showed an improvement of 0.0118 db. In Column 6 the shortest waveguide of each type is used as a reference for insertion loss, and insertion losses for the longer lengths of waveguide are calculated by taking the ratio of the lengths. Comparing the loss values obtained in this manner with the losses measured in February 1963 (Column 3), Column 7 is obtained. The differences in Column 7 are small with the exception of the value obtained for the longest stainless-steel waveguide. The 0.008-db difference for that waveguide is believed to be real and not a measurement error.

Additional standards used to check the accuracy and precision of the insertion loss set were provided by high-precision rotary vane attenuators. The rotary vane attenuator is an excellent variable attenuation standard for very low and high attenuation values. Specially devel-

Table 2. 12.00-in. copper waveguide: insertion loss at 8.448 Gc

0 = 0.8944 = 0.4847 db	
Test = 0.8857 = 0.5271	0.0424 db
0 = 0.8944 = 0.4847	0.0424
Test = 0.8861 = 0.5252	0.0405
0 = 0.8944 = 0.4847	0.0405
Test = 0.8863 = 0.5242	0.0395
0 = 0.8949 = 0.4823	0.0419
6	0.2472
Average loss =	0.0412 db ± 0.0011 standard deviation

oped S- and H-band rotary vane attenuators were used. Comparisons of theoretical and measured attenuation values were made at 2388 and 8448 Mc.

C. S-Band Rotary Vane Attenuator

A photograph of the special S-band rotary vane attenuator and measurement system may be seen in Fig. 7. The end sections of the attenuator are WR430 to WC385 transitions. The basic attenuator was fabricated to JPL design specifications by the Microwave Components and Systems Corporation, Monrovia, California. The attenuator is rugged in its construction and was designed to enable high-precision readout of the rotary vane angle. The rotor is gear-driven by a 28-vdc motor. The vane angle can be read on a Veeder-Root counter which can be resolved to 0.001 deg. It was found from electrical tests that the resetability of the vane is about ±0.002 deg if the rotor is always driven in the same direction. The backlash was determined from electrical tests to be about 0.02 deg. The gearing and readout system was fabricated by Ellison Engineering, Glendale, California.

If the attenuator gearing and readout system possesses no errors, the vane angle position relative to the zero-deg setting should be indicated correctly on the Veeder-Root counter. However, because of possible bearing runouts and eccentricity errors in the gear train which drives the counter, some angular readout errors will occur at various vane angle settings. For this attenuator, the bearing runouts were less than 0.002 in. (radial and axial). Calibration of the actual rotor angular position vs indicated vane angles was performed by the JPL Mechanical Inspection Department. An error analysis of the method indicated that the accuracy of the angular calibration was probably within ±0.015 deg (Ref. 10). The readout

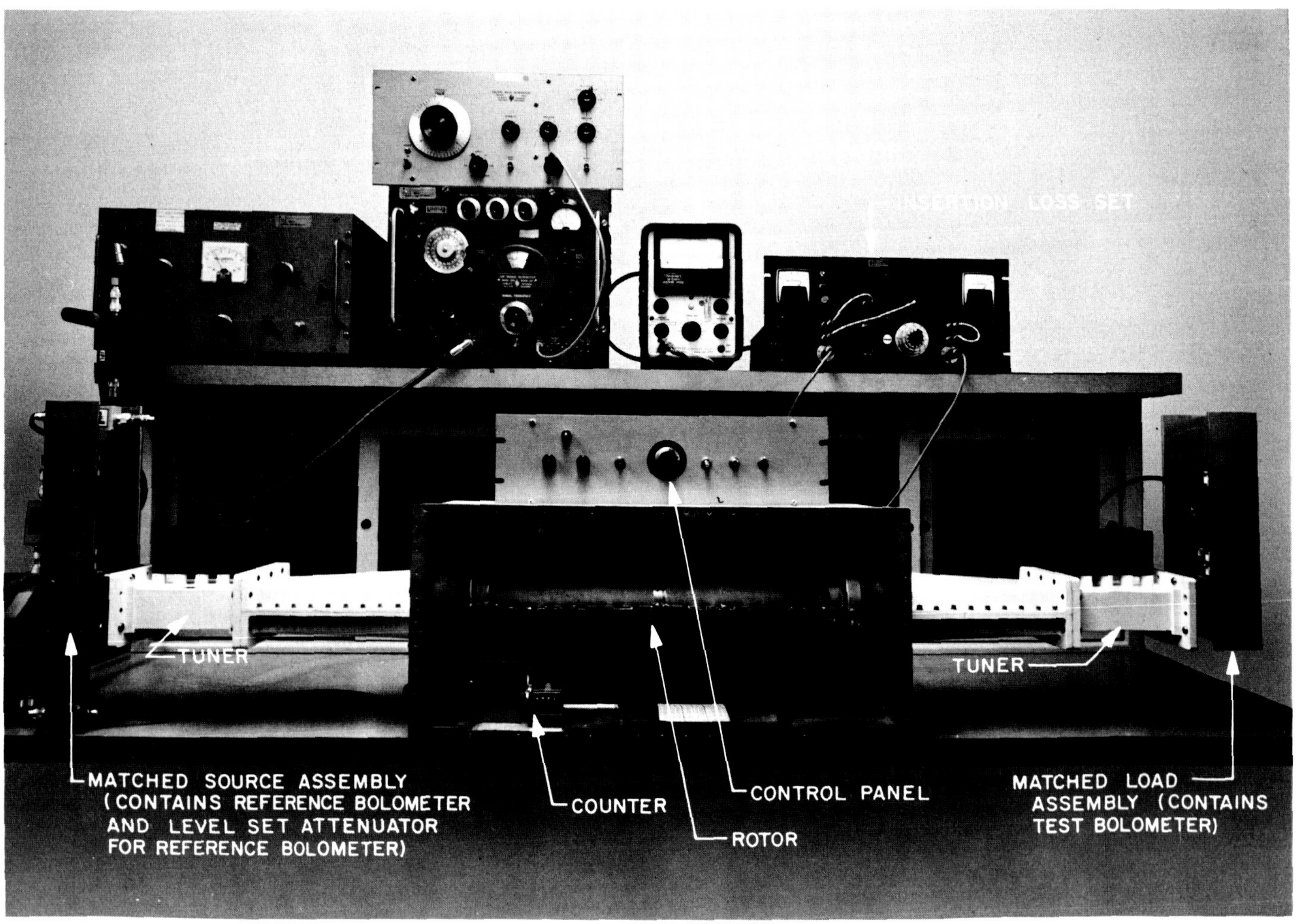

Fig. 7. S-band rotary vane attenuator and ac ratio transformer insertion loss set

errors of the attenuator were determined and used to correct the theoretical attenuation values which corresponded to the indicated vane angles.

For the attenuation measurements, the VSWRs of the source and load assemblies of the measurement system were matched to 1.01 or less. The measured attenuator VSWR as a function of vane angle may be seen in Fig. 8.

The particular bolometers and bolometer mounts used in the insertion loss test set were the Narda N603 and 561F types, respectively. For calibration of the rotary vane attenuator, the reference and test bolometers were operated at rf power levels of less than 0.05 mw average power (or 0.1 mw peak power). The 0.05-mw limit was determined experimentally as being a suitable operating limit for minimizing bolometer nonlinearity errors (Ref. 11).

Table 3 shows the results of attenuation measurements made with the ac ratio transformer test set operated over a 30-db dynamic range at 2388 Mc. The deviations between corrected theoretical and measured results for attenuations greater than 10 db are believed to be principally due to bolometer nonlinearity errors and loss of precision of setting the ratio transformer dial on the null. Also, for attenuation measurements corresponding to very small ratios of the order of 10^{-3}, the limiting accuracy of

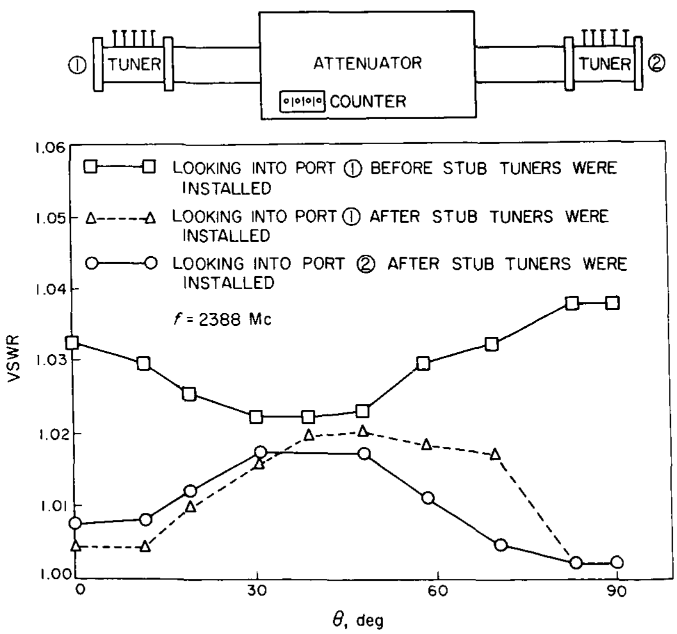

Fig. 8. VSWR vs angular rotation characteristics of the S-band rotary vane attenuator

Table 3. AC ratio transformer insertion loss set operated over a 30-db dynamic range at 2388 Mc

Rotary vane theoretical attenuation, db	Corrected theoretical attenuation, db	Measured attenuation, db	Deviation, db
10	10.0178	10.0161	+0.0017
20	20.0382	20.0555	−0.0173
25	25.0597	25.1070	−0.0473
30	30.0706	30.2271	−0.1565

1 part in 10^5 of the particular ratio transformer used (ESI DT-45) could have contributed errors of the order of ± 0.04 to ± 0.05 db. The use of ratio transformers which have accuracies of 1 part in 10^6 would have reduced possible ratio transformer errors to about ± 0.005 db for a 30-db attenuation measurement.

For calibration of the rotary vane attenuator, the measurement method used was to measure db attenuation differences between reference and indicated vane angle settings. The maximum attenuation difference measured in one step with the ac ratio transformer set was purposely restricted to 10 or 20 db (Ref. 11). At each new reference vane angle setting, the average rf power levels at the reference and test bolometers were reset to 0.05 mw. Table 4 shows comparisons of apparent theoretical, corrected theoretical, and average measured attenuations relative to the 0-db setting at 2388 Mc. The average measured attenuations are the result of three runs and were compiled from data obtained from measurements of attenuation differences. A high degree of resolution and repeatability of data was made possible by the resetability of the rotary vane and the precision readout of the ac ratio transformer insertion loss set. Typical precision of the measurement is indicated by maximum deviations of $+0.0002/-0.0004$ db from the average measured value at the 10-db setting (Ref. 11). Comparison of the corrected theoretical attenuation to the measured attenuation shows very good agreement over a 60-db range.

Table 5 presents an estimate of the limits of the cumulative measurement error in the calibration method, while Table 6 shows limits of errors of the rotary vane attenuator which could cause deviations from the theoretical corrected attenuation. The errors shown in Table 6 are defined in a paper by A. V. James (Ref. 12) and are based on other preliminary data taken at JPL (Ref. 11).

Table 4. Comparison of theoretical and measured attenuations for the S-band rotary vane attenuator at 2388 Mc

Indicated vane angle θ_i, deg	Apparent theoretical attenuation A_i, db	Measured vane angle[a] θ_v, deg	Indicated vane angle error $(\theta_v - \theta_i)$, deg	Corrected theoretical attenuation A_v, db	Average measured attenuation[b] A_m, db	Average measured deviation from corrected attenuation $(A_v - A_m)$, db
2.749	0.0200	2.755	+0.006	0.0201	0.0197	+0.0004
3.887	0.0400	3.887	0.000	0.0400	0.0394	+0.0006
4.759	0.0600	4.761	0.002	0.0601	0.0595	+0.0006
5.495	0.0800	5.499	0.004	0.0801	0.0793	+0.0008
6.142	0.1000	6.146	0.004	0.1001	0.0993	+0.0008
8.678	0.2000	8.684	0.006	0.2003	0.1995	+0.0008
12.248	0.4000	12.258	0.010	0.4007	0.3993	+0.0014
14.972	0.6000	14.989	0.017	0.6014	0.5993	+0.0021
17.255	0.8000	17.271	0.016	0.8015	0.7989	+0.0026
19.255	1.0000	19.272	0.017	1.0018	1.0015	+0.0003
26.969	2.0000	26.987	0.018	2.0028	2.0039	−0.0011
32.712	3.0000	32.734	0.022	3.0043	3.0060	−0.0017
37.408	4.0000	37.429	0.021	4.0049	4.0075	−0.0026
41.419	5.0000	41.446	0.027	5.0072	5.0088	−0.0016
44.932	6.0000	44.964	0.032	6.0097	6.0105	−0.0008
48.061	7.0000	48.095	0.034	7.0115	7.0115	0.0000
50.879	8.0000	50.911	0.032	8.0119	8.0125	−0.0006
53.440	9.0000	53.476	0.036	9.0147	9.0162	−0.0015
55.782	10.0000	55.822	0.040	10.0178	10.0159	+0.0019
59.921	12.0000	59.955	0.034	12.0178	12.0196	−0.0018
63.469	14.0000	63.505	0.036	14.0219	14.0259	−0.0040
66.540	16.0000	66.578	0.038	16.0266	16.0285	−0.0019
69.218	18.0000	69.257	0.039	18.0312	18.0318	−0.0006
71.565	20.0000	71.607	0.042	20.0382	20.0353	+0.0029
76.282	25.0000	76.330	0.048	25.0597	25.0576	+0.0021
79.757	30.0000	79.799	0.042	30.0706	30.0696	+0.0010
82.337	35.0000	82.381	0.044	35.0994	35.0930	+0.0064
84.261	40.0000	84.306	0.045	40.1363	40.1273	+0.0090
85.699	45.0000	85.758	0.059	45.2395	45.1566	+0.0829
86.776	50.0000	86.829	0.053	50.2877	50.1737	+0.1140
87.583	55.0000	87.632	0.049	55.3556	55.1812	+0.1744
88.188	60.0000	88.242	0.054	60.5254	60.1989	+0.3265
88.641	65.0000	88.693	0.052	65.6777	---	---
88.981	70.0000	89.031	0.050	70.8740	---	---

[a] Measured by the JPL Mechanical Inspection Department. For discussion of the vane angle measurement method, see Ref. 10.
[b] See Table 5 of Ref. 11.

Table 5. Estimated cumulative measurement errors in calibrating the rotary vane attenuator

Indicated vane angle setting, deg	Average measured attenuation, db	Cumulative resetability error, db	Other estimated measurement errors,[a] db	Total error, db
55.782	10.0159	±0.0009	±0.010	±0.0109
71.565	20.0353	±0.0027	±0.020	±0.0227
79.757	30.0696	±0.0061	±0.030	±0.0361
84.261	40.1273	±0.0087	±0.050	±0.0581
86.776	50.1737	±0.0195	±0.060	±0.0795
88.188	60.1989	±0.0279	±0.080	±0.1079

[a] Includes estimate of the ac ratio transformer test set inaccuracy and probable bolometer nonlinearity errors in the calibration. Errors caused by external mismatch are included in Table 6.

Table 6. Summary of rotary vane attenuator errors causing deviation from the corrected theoretical attenuations

Indicated vane angle setting, deg	Corrected theoretical attenuation, db	Uncertainty in vane angle corrections,[a] db	External mismatch error, db	Internal mismatch error, db	Transmission error, db	Alignment error, db	Total error, db
55.782	10.0178	±0.0067	±0.0006	±0.0027	±0.0006	...	±0.0106
71.565	20.0382	±0.0137	±0.0005	±0.0035	±0.0025	±0.0001	±0.0203
79.757	30.0706	±0.0253	±0.0003	±0.0038	±0.0084	±0.0002	±0.0380
84.261	40.1363	±0.0457	±0.0003	±0.0039	±0.0271	±0.0007	±0.0777
86.776	50.2877	±0.0823	±0.0003	±0.0039	±0.0862	±0.0021	±0.1748
88.188	60.5254	±0.1488	±0.0003	±0.0039	±0.2702	±0.0066	±0.4298

[a] Based on ±0.015-deg tolerances on the accuracy of the vane angle measurements.

It may be seen that, at the 60-db indicated vane angle setting, the measured attenuation and estimated measurement error is 60.1989 ± 0.1079 db, while the corrected theoretical attenuation value and possible deviation is 60.5254 ± 0.4298 db. The same attenuator was calibrated independently using a dc substitution technique (Ref. 13). For attenuation values up to 6 db, the results of that calibration agreed within ±0.003 db with measured values shown in Table 4.

D. H-Band Rotary Vane Attenuator

Similar tests were also made at 8448 Mc on a Hewlett-Packard H382A rotary vane attenuator which was modified to permit readout of the rotary vane angle in degrees, minutes, and seconds. The gearing and readout system for this attenuator was designed by the Measurement Specialties Laboratory, Inc., Van Nuys, California. The attenuator and test setup are shown in Fig. 9. For attenuation measurements at this frequency, the detectors and detector mounts used were the Sperry 821 barretters and Hewlett-Packard Model H485B detector mounts, respectively. The theoretical and average measured attenuations agreed to within ±0.005 db for attenuations up to 6 db and ±0.015 db for attenuations up to 20 db. Analysis of the measured and theoretical values over a 40-db range indicated that the deviations were probably due to angular readout errors (Ref. 14).

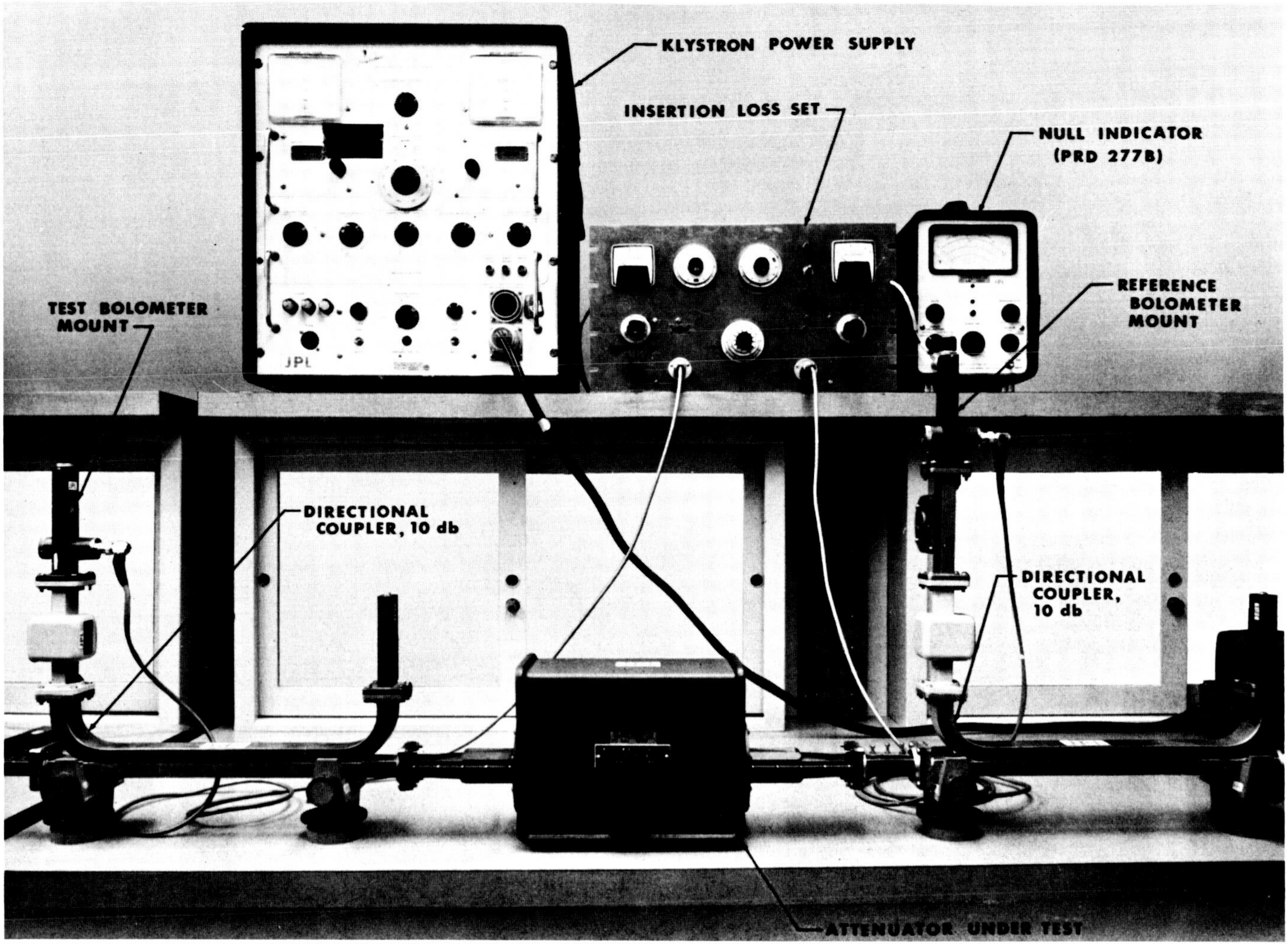

Fig. 9. H-band rotary vane attenuator and measurement system

IV. CONCLUSIONS

A simple, high-precision, portable insertion loss device has been developed which can be made to approach the accuracy of a high-quality standard ratio transformer. It is believed that an accuracy of ± 0.003 db has been obtained for a measurement of about 0.5 db. The 0.003 db is believed to be the total probable error, including error due to mismatch and to connecting and disconnecting flanges. Measurements may be made of insertion loss values up to 20 to 30 db in one step, subject to the normal bolometer linearity limitations. With care, accuracies of a few hundredths db in 30 db may be obtainable.

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